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FUNDAMENTAL ASPECTS OF GASEOUS BREAKDOWN–II

We continue the discussion of gaseous breakdown shifting our emphasis to the study of phenomena in both uniform and non-uniform electrical fields. We begin with the electron energy distribution function (EEDF) which is one of the most fundamental aspects of electron motion in gases. Recent advances in calculation of the EEDF have been presented, with details about Boltzmann equation and Monte Carlo methods. The formation of streamers in the uniform field gap with a moderate over-voltage has been described. Descriptions of Electrical coronas follow in a logical manner. The earlier work on corona discharges has been summarized in several books^{1, 2} and we shall limit our presentation to the more recent literature on the subject. However a brief introduction will be provided to maintain continuity.

9.1 ELECTRON ENERGY DISTRIBUTION FUNCTIONS (EEDF)

One of the most fundamental aspects of gas discharge phenomena is the determination of the electron energy distribution (EEDF) that in turn determines the swarm parameters that we have discussed briefly in section (8.1.17). It is useful to recall the integrals that relate the collision cross sections and the energy distribution function to the swarm parameters. The ionization coefficient is defined as:

$$\frac{\alpha}{N} = \frac{1}{W} \left(\frac{2e}{m} \right) E \int_{\varepsilon_i}^{\infty} \varepsilon^{1/2} Q_i(\varepsilon) F(\varepsilon) d\varepsilon \quad (9.1)$$

in which e/m is the charge to mass ratio of electron, $F(\varepsilon)$ is the electron energy distribution function, ε the electron energy, ε_i the ionization potential and $Q_i(\varepsilon)$ the

ionization cross section which is a function of electron energy. Other swarm parameters are similarly defined. It is relevant to point out that the definition of (9.1) is quite general and does not specify any particular distribution. In several gases $Q_i(\epsilon)$ is generally a function of ϵ according to (Fig. 8.4),

$$Q_i = \frac{Q_i^0 (\epsilon - \epsilon_i)^n}{\epsilon} \quad (9.2)$$

Substitution of Maxwellian distribution function for $F(\epsilon)$, equation (1.92) and equation (9.2) in eq. (9.1) yields an expression similar to (8.11) thereby providing a theoretical basis³ for the calculation of the swarm parameters.

9.1.1 EEDF: THE BOLTZMANN EQUATION

The EEDF is not Maxwellian in rare gases and large number of molecular gases. The electrons gain energy from the electric field and lose energy through collisions. In the steady state the net gain of energy is zero and the Boltzmann equation is universally adopted to determine EEDF. The Boltzmann equation is given by⁴:

$$\frac{\partial}{\partial t} F(\mathbf{r}, \mathbf{v}, t) + \mathbf{a} \cdot \nabla_{\mathbf{v}} F(\mathbf{r}, \mathbf{v}, t) + \mathbf{v} \cdot \nabla_{\mathbf{r}} F(\mathbf{r}, \mathbf{v}, t) = J[F(\mathbf{r}, \mathbf{v}, t)] \quad (9.3)$$

where F is the EEDF and J is called the collision integral that accounts for the collisions that occur. The solution of the Boltzmann equation gives both spatial and temporal variation of the EEDF. Much of the earlier work either used approximations that rendered closed form solutions or neglected the time variation treating the equation as integro-differential. With the advent of fast computers these are of only historical importance now and much of the progress that has been achieved in determining EEDF is due to numerical methods.

The solution of the Boltzmann equation gives the electron energy distribution (EEDF) from which swarm parameters are obtained by appropriate integration. To find the solution the Boltzmann equation may be expanded using spherical harmonics or the Fourier expansion. If we adopt the spherical harmonic expansion then the axial symmetry of the discharge reduces it to Legendre expansion and in the first approximation only the first two terms may be considered. The criterion for the validity of the two term expansion is that the inelastic collision cross sections must be small with respect to the elastic collision cross sections or that the energy loss during elastic

collisions should be small. These assumptions may not be strictly valid in molecular gases where inelastic collisions occur with large cross sections at low energies due to vibration and rotation. The two-term solution method is easy to implement and several good computer codes are available⁵.

The Boltzmann equation used by Tagashira et. al.⁶ has the form

$$\frac{\partial}{\partial t} \int_0^{\infty} n(\varepsilon', z, t) d\varepsilon' = N_c + N_E + N_z \quad (9.4)$$

where $n(\varepsilon', z, t)$ is the electron number density with (ε', z, t) as the energy, space and time variables, respectively, N_c , N_E and N_z are the change rate of electron number density due to collision, applied electric field and gradient, respectively. Equation (9.4) has a simple physical meaning: the electron number density is conserved. The solution of equation (9.4) may be written in the form of a Fourier expansion⁷:

$$n_s(\varepsilon, z, t) = e^{isz} e^{-w(s)t} H_o(\varepsilon, s) \quad (9.5)$$

where s is the parameter representing the Fourier component and

$$w(s) = -w_0 + w_1(is) - w_2(is)^2 + w_3(is)^3 \dots \quad (9.6)$$

$$H_o(\varepsilon, s) = f_o(\varepsilon) + f_1(\varepsilon)(is) + f_2(\varepsilon)(is)^2 + \dots \quad (9.7)$$

where w_n ($n = 0, 1, 2, \dots$) are constants. The method of obtaining the solution is described by Liu [7]. The method has been applied to obtain the swarm parameters in mercury vapor and very good agreement with the Boltzmann method is obtained. The literature on Application of Boltzmann equation to determine EEDF is vast and, as an example, Table 9.1 lists some recent investigations in oxygen⁸.

9.1.2 EEDF: THE MONTE CARLO METHOD

The Monte Carlo method provides an alternative method to the Boltzmann equation method for finding EEDF (Fig. 9.1). and this method has been explored in considerable detail by several groups of researchers, led by, particularly, Tagashira, Lucas and Govinda Raju. The Monte Carlo method does not assume steady state conditions and is therefore responsive to the local deviations from the energy gained by the field. Different methods are available.

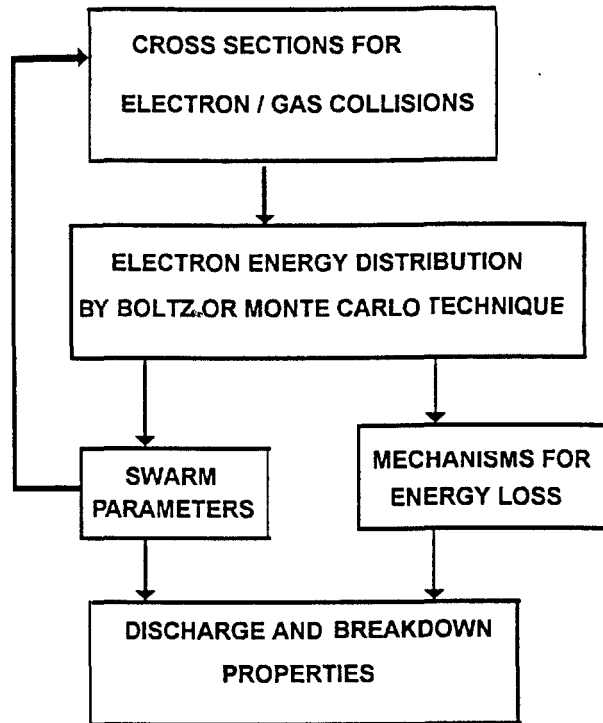


Fig. 9.1 Methods for determining EEDF and swarm parameters

A. MEAN FREE PATH APPROACH

In a uniform electric field an electron moves in a parabolic orbit until it collides with a gas molecule. The mean free path λ (m) is

$$\lambda = \frac{1}{NQ_t(\varepsilon)} \quad (9.8)$$

where Q_t is the total cross section in m^2 and ε the electron energy in eV. Since Q_t is a function of electron energy, λ is dependent on position and energy of the electron. The mean free path is divided into small fractions, $ds = \lambda / a$, where a is generally chosen to be between 10 and 100 and the probability that an electron collides with gas molecules in this step distance is calculated as $P_1 = ds/\lambda$. The smaller the ds is chosen, the longer the calculation time becomes although we get a better approximation to simulation. The collision event is decided by a number of random numbers, each representing a particular type.

B. MEAN FLIGHT TIME APPROACH

The mean flight time of an electron moving with a velocity $W(\epsilon)$ is

$$T_m = \frac{1}{NQ_T(\epsilon)W(\epsilon)} \quad (9.9)$$

where $W(\epsilon)$ is the drift velocity of electrons. The time of flight is divided into a number of smaller elements according to

$$dt = \frac{T_m}{K} \quad (9.10)$$

where K is a sufficiently large integer.

The collision frequency may be considered to remain constant in the small interval dt and the probability of collision in time dt is

$$P = 1 - \exp\left[-\frac{dt}{T_m}\right] \quad (9.11)$$

For each time step the procedure is repeated till a predetermined termination time is reached. Fig. (9.2) shows the distribution of electrons and energy obtained from a simulation in mercury vapour.

C. NULL COLLISION TECHNIQUE

Both the mean free path and mean collision time approach have the disadvantage that the CPU time required to calculate the motion of electrons is excessively large. This problem is simplified by using a technique known as the null collision technique. If we can find an upper bound of collision frequency $\nu_{\max}$ such that

$$\nu_{\max} = \max[NQ_T(\epsilon)W(\epsilon)] \quad (9.12)$$

and the constant mean flight time is $1/\nu_{\max}$ the actual flight time is

$$dt = -\frac{\ln R}{v_{\max}} \quad (9.13)$$

where R is a random number between 0 and 1.

Table 9.1

Boltzmann Distribution studies in oxygen. The parameters calculated are indicated. W = Drift velocity of electrons, ε_m = mean energy, ε_k = characteristic energy, η = attachment co-efficient, α = ionization co-efficient, $f(\varepsilon)$ = electron energy distribution, $\times$ denotes the quantities calculated [Liu and Raju, 1995].

Author	E/N (Td)	W	ε_m	ε_k	η	α	$f(\varepsilon)$
Hake et. al. ⁹	0.01-150	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$
Myers ¹⁰	10^{-3} -200		$\times$	$\times$			
Wagner ¹¹	90-150				$\times$	$\times$	
Lucas et. al. ¹²	15-152	$\times$	$\times$		$\times$	$\times$	$\times$
Masek ¹³	1-140	$\times$	$\times$	$\times$		$\times$	$\times$
Masek et. al. ¹⁴	1-200	$\times$	$\times$	$\times$			$\times$
Masek et. al. ¹⁵	10-200				$\times$		$\times$
Taniguchi et. al. ¹⁶	1-30				$\times$		
Gousset et. al. ¹⁷	0.1-130	$\times$	$\times$	$\times$		$\times$	$\times$
Taniguchi et. al. ¹⁸	0.1-20	$\times$			$\times$		$\times$
Liu and Raju (1993)	20-5000	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$

The assumed total collision cross section Q_t is

$$Q_T = Q_T + Q_{null} \quad (9.14)$$

where Q_{null} is called the null collision cross section.

We can determine whether the collision is null or real after having determined that a collision takes place after a certain interval dt . If the collision is null we proceed to the next collision without any change in electron energy and direction. In the mean free path and mean flight time approaches, the motion of electrons is followed in a time scale of T_m / k while in the null collision technique it is on the T_m scale. The null collision technique is computationally more efficient but it has the disadvantage that it cannot be used in situations where the electric field changes rapidly.

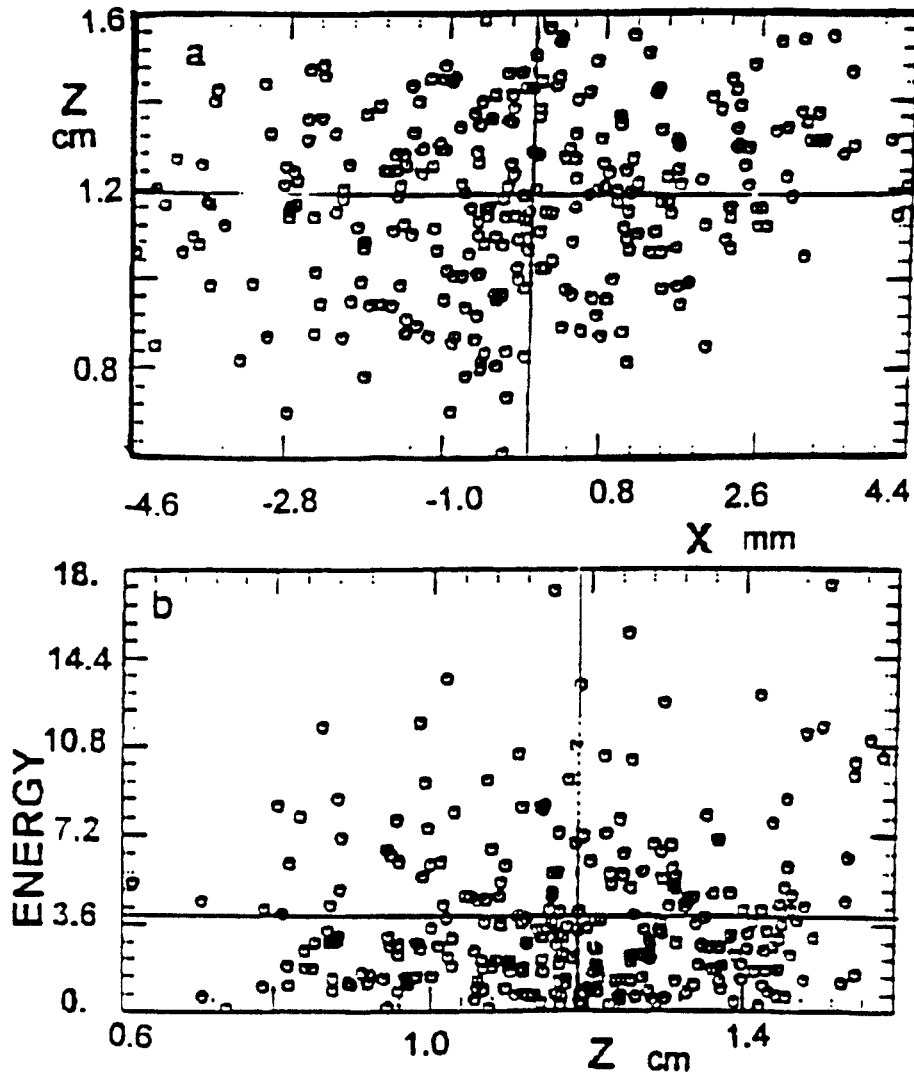


Fig. 9.2 Distribution of electrons and energy in mercury vapour as determined in Monte-Carlo simulation, $E/N = 420$ Td. $T = 40$ ns [Raju and Liu, 1995, with permission of IEEE ©.]

D. MONTE CARLO FLUX METHOD

In the techniques described above, the electron trajectories are calculated and collisions of electrons with molecules are simulated. The swarm parameters are obtained after following one or a few electrons for a predetermined period of distance or time. A large number of electrons are required to be studied to obtain stable values of the coefficients, demanding high resolution and small CPU time, which are mutually contradictory. The problem is particularly serious at low and high electron energies at which the distribution function tends to have small values. To overcome these difficulties Schaffer and Hui¹⁹ have adopted a method known as the Monte Carlo flux method which is based on the

concept that the distribution function is renormalized by using weight factors which have changing values during the simulation. The low energy and high energy part of the distribution are also redetermined in a separate calculation.

The major difference between the Monte Carlo flux method and the conventional technique is that, in the former approach, the electrons are not followed over a long period of time in calculating the transition probabilities, but only over a sampling time t_s . One important feature of the flux method is that the number of electrons introduced into any state can be chosen independent of the final value of the distribution function. In other words, we can introduce as many electrons into any phase cell in the extremities of the distribution as in other parts of the distribution.

The CPU time for both computations is claimed to be the same as long as the number of collisions are kept constant. The conventional method has good resolution in the ranges of energy where the distribution function is large, but poorer resolution at the extremities. The flux method has approximately the same resolution over the full range of phase space investigated. Table 9.2 summarizes some recent applications of the Monte Carlo method to uniform electric fields.

9.2 STREAMER FORMATION IN UNIFORM FIELDS

We now consider the development of streamers in a uniform field in SF_6 at small overvoltages ~ 1 -10%. In this study 1000 initial electrons are released from the cathode with 0.1 eV energy²⁰. During the first 400 time steps the space charge field is neglected. If the total number of electrons exceeds 10^4 , a scaling subroutine chooses 10^4 electrons out of the total population. In view of the low initial energy of the electron, attachment is large during the first several steps and the population of electrons increases slowly. At electron density of $2 \times 10^{16} \text{ m}^{-3}$ space charge distortion begins to appear. The electric field behind and ahead of the avalanche is enhanced, while in the bulk of the avalanche the field is reduced.

In view of the large attachment the number of electrons is less than that of positive ions, and the field behind the avalanche is enhanced. On the other hand, the maximum field enhancement in a non-attaching gas occurs at the leading edge of the avalanche. The development of streamers is shown in Fig. 9.3. As the first avalanche moves toward the anode, its size grows. The leading edge of the streamer propagates at a speed of $6.5 \times 10^5 \text{ ms}^{-1}$. The trailing edge has a lower velocity $\sim 2.9 \times 10^5 \text{ ms}^{-1}$. At $t = 1.4 \text{ ns}$, the primary streamer slows down (at A) by shielding itself from the applied field.

Table 9.2

Monte Carlo Studies in Uniform Electric Fields (Liu and Raju, (©1995, IEEE)

GAS	AUTHORS	RANGE (Td)	REFERENCE
N ₂	Kucukarpaci and Lucas	$14 \leq E/N \leq 3000$	J. Phys. D.: Appl. Phys. 12 (1979) 2123-2138
	Schaffer and Hui	$50 \leq E/N \leq 300$	J. Comp. Phys. 89 (1990) 1-30
	Liu and Raju	$20 \leq E/N \leq 2000$	J. Frank. Inst. 329 (181-194) 1992; IEEE Trans. Elec. Insul. 28 (1993) 154-156.
	Lucas & Saelee	$14 \leq E/N \leq 3000$	J. Phys. D.: Appl. Phys. 8 (1975) 640-650.
	Mcintosh Raju and Dincer	$E/N = 3$ $240 \leq E/N \leq 600$	Austr. J. Phys. 27 (1974) 59-71. IEEE Trans. on Plas. Sci., 17 (1990) 819-825
O ₂	Liu and Raju	$20 \leq E/N \leq 2000$	IEEE Trans. Elec. Insul. 28 (1993) 154-156.
	Al Amin et. al	$25.4 \leq E/N \leq 848$	J. Phys. D.: Appl. Phys. 18 (1985) 1781-1794
air	Liu and Raju	$20 \leq E/N \leq 2000$	IEEE Trans. Elec. Insul. 28 (1993) 154-156.
CH ₄	Al Amin et. al	$25.4 \leq E/N \leq 848$	J. Phys. D.: Appl. Phys. 18 (1985) 1781-1794
Ar	Kucukarpaci and Lucas	$141 \leq E/N \leq 566$	J. Phys. D.: Appl. Phys. 14 (1981) 2001-2014.
	Sakai et. al.	$E/N=141, 283, 566$	J. Phys. D.: Appl. Phys. 10 (1995) 1035-1049.
Kr	Kucukarpaci and Lucas	$141 \leq E/N \leq 566$	J. Phys. D.: Appl. Phys. 18 (1985) 1781-1794
CO ₂	Kucukarpaci and Lucas	$14 \leq E/N \leq 3000$	J. Phys. D.: Appl. Phys. 12 (1979) 2123-2138
H ₂	Hunter	$1.4 \leq E/N \leq 170$	Austr. J. Phys., 30 (1977) 83-104
	Read & Hunter	$0.5 \leq E/N \leq 200$	Austr. J. Phys., 32 (1979) 255-259
	Blevin et. al	$40 \leq E/N \leq 200$	J. Phys. D.: Appl. Phys. 11 (1978) 2295-2303.
Hg	Hayashi	$3 \leq E/N \leq 3000$	J. de Physique. C740 (1979) 45-46
	Liu & Raju	$10 \leq E/N \leq 2000$	J. Phys. D.: Appl. Phys. 25 (1992) 167-172
	Nakamura and Lucas	$0.7 \leq E/N \leq 50$	J. Phys. D.: Appl. Phys. 11 (1978) 337-345.
SF ₆	Dincer and Raju	$300 \leq E/N \leq 540$	J. Appl. Phys., 54 (1983) 6311-6316
He	Braglia and Lowke	$E/N = 1$	J. de Physique C740 (1979) 17-18
	Liu and Raju	$200 \leq E/N \leq 700$	IEEE Trans. on Plas. Sci., 20 (1992) 515-524
Na	Lucas	$30 \leq E/N \leq 150$	Int. J. Electronics, 32 (1972) 393-410
	Lucas	$0.7 \leq E/N \leq 50$	J. Phys. D.,Appl. Phy. 11 (1978) 337-345

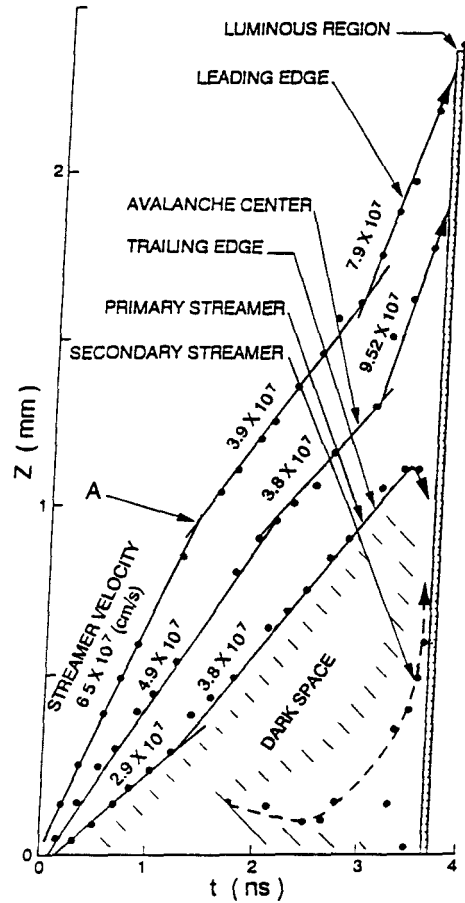


Fig. 9.3 Streamer development and calculated luminosity vs position and time in a uniform electric field at 7% over voltage (Liu and Raju, © 1993, IEEE)

The velocity of the leading edge decreases to $3.9 \times 10^5 \text{ ms}^{-1}$; however the trailing edge propagates faster than before, at $3.8 \times 10^5 \text{ ms}^{-1}$. The enhanced field between the cathode and the primary streamer is responsible for this increase in velocity. The secondary streamer, caused by photo-ionization, occurs at $t = 2 \text{ ns}$ and propagates very fast in the maximum enhanced field between the two streamers. The secondary streamer moves very fast and connects with the primary streamer within $\sim 0.2 \text{ ns}$. The observed dark space exists for $\sim 2 \text{ ns}$. These results explain the experimentally observed dark space by Chalmers et. al.²¹ in the centre of the gap at 4% over-voltage. Between the primary and secondary streamer there is a dark space, shown hatched in Fig. 9.3.

The theoretical simulation of discharges that had been carried out till 1985 are summarized by Davies²². The two dimensional continuity equation for electron, positive ion and excited molecules in He and H₂ have been considered by Novak and Bartnikas^{23, 24, 25, 26}. Photoionization in the gap was not considered, but photon flux, ion flux and metastable flux to cathode as cathode emission were included. The continuity equations

were solved by finite element method. Because of the steep, shock-like density gradients the solution by ordinary finite difference method is difficult and is limited to the early stages of streamer formation. Dhali and Pal²⁷ in SF₆ and Dhali and Williams²⁸ in N₂ handle the steep density gradients by using flux-corrected transport techniques which improved the numerical method for the two dimensional continuity equations.

9.3 THE CORONA DISCHARGE

Due to the technological importance of corona in electrophotography, partial discharges in cables, applications in the treatment of gaseous pollutants, pulsed corona for removing volatile impurities from drinking water etc. (Jayaram et. al., 1996), studies on corona discharge continue to draw interest. Corona is a self sustained electrical discharge in a gas where the Laplacian electric field confines the primary ionization process to regions close to high field electrodes. When the electric field is non-uniform, as exists in an asymmetrical electrode geometry (Fig. 9.4), the collision processes near the smaller electrode will be more intense than in other regions of the gap.

The non-uniformity of the electric field results in a partial breakdown of the gap. This phenomenon is called the electrical corona. The inter electrode gap may be divided into several regions²⁹, viz., (1) Glow region very close to the active (high voltage) electrode, (2) The drift region where ionization does not occur because of the low electric field and charge carriers drift in the field (3) charge free region which is separated by the active region by the Laplacian boundary.

The domain of the individual regions varies depending on the configuration of the electrode geometry, the characteristics of the insulating gas and the magnitude of the applied voltage which may or may not be time dependent. The existence of a charge-free region is not certain in all electrode configurations; for example in a concentric cylinder geometry we have only the glow and drift region. Depending upon the polarity of the smaller electrode the discharge that occurs in different manifestations though the Laplacian electric field is independent of the polarity.

In the active region, ionization by collision occurs and a self maintained discharge exists at sufficiently high voltage when according to the Townsend's criterion, $\gamma \exp\left(\int_0^{d_0} \alpha dx\right) = 1$ where d_0 is the edge of the glow region. The integral is used because the electric field is spatially varying and therefore the Townsend's first ionization coefficient is not constant.

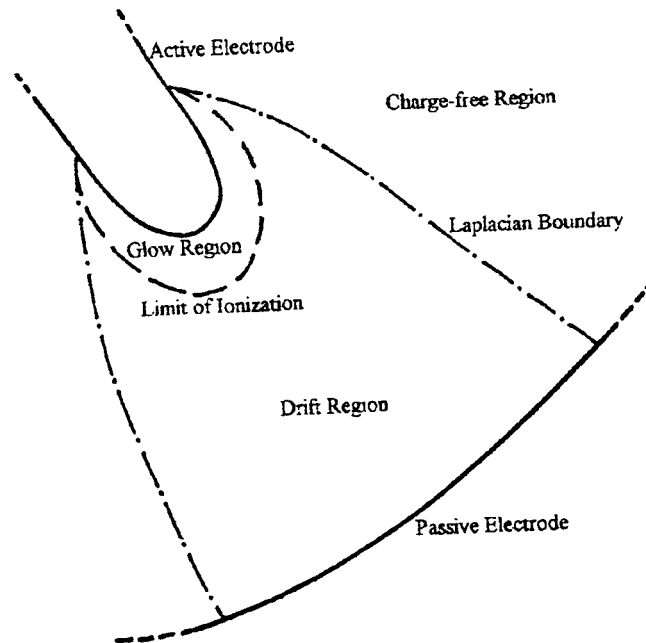


Fig. 9.4 Schematic description of regions in a corona discharge. The boundaries of the three regions vary depending upon the electrode dimension and shape of the electrode [Jones, 2000] (With permission of the Institute of Physics, England).

9.4 BASIC MECHANISMS : NEGATIVE CORONA

Negative coronas in gases have been studied quite extensively and there is general agreement on the broad characteristics of corona discharge in common gases like air, oxygen, etc. and rare gases such as argon and helium (Loeb, 1965). In electronegative gases the negative corona is in the form of regular pulses, called Trichel pulses. The pulses have a very fast rise time ($\sim$ ns) and short duration with a long period of relatively low current between the pulses. In oxygen and air the pulses are extremely regular, increasing in frequency with the corona discharge current. Sharper points have a higher frequency for the same corona current.

In SF_6 the initial corona current in a negative point plane gap flows in the form of intermittent pulses³⁰. The frequency of the pulses depends on the magnitude of the corona current and not on the gap length. Further, for the same corona current the frequency is higher for a sharper point. The frequency increases approximately linearly with the average corona current and at very high currents the pulses occur so rapidly that they merge into each other forming a glow; the current now becomes continuous.

An early explanation for the high frequency pulses in a negative point-plane was given by Loeb (1965) in terms of the space charge, and it is still valid in its broad features. Near the point electrode the electron avalanches produce a positive ion space charge that increases exponentially with distance from the point electrode. At some finite distance from the tip of the point electrode the electric field, which decreases with increasing distance, becomes low enough to make attachment a dominant process. The resulting negative ion space charge thus formed chokes off the current during the time necessary for most of the ions to be swept away to the positive electrode.

After the negative ions are cleared a new pulse is initiated at the negative electrode with the process repeating itself. Figure 9.5 shows the space charge and potential near the tip of the electrode at the instant the corona pulse is extinguished, (a), and the instant at which the negative space charge is nearly cleared, (b). The top Figure shows the presence of positive ions closer to the electrode and the negative ions farther away. The distortion of the Laplacian electric field due to the space charges are also shown. Close to the point there is intensification of the field due to the positive ions and a corresponding reduction in the field in the region of negative ion space charge. At (b), conditions just before clearing of the space charge and reinstatement of the Laplacian field are shown.

In view of its technological importance, the corona in SF_6 has attracted considerable interest for understanding the mechanisms, and a typical experimental set up used by Van Brunt and Leap (1981) is shown in Figure 9.6. A significant observation is that the negative corona critically depends on the point electrode surface which is not surprising because the initiatory electrons originate from the electrode surface.

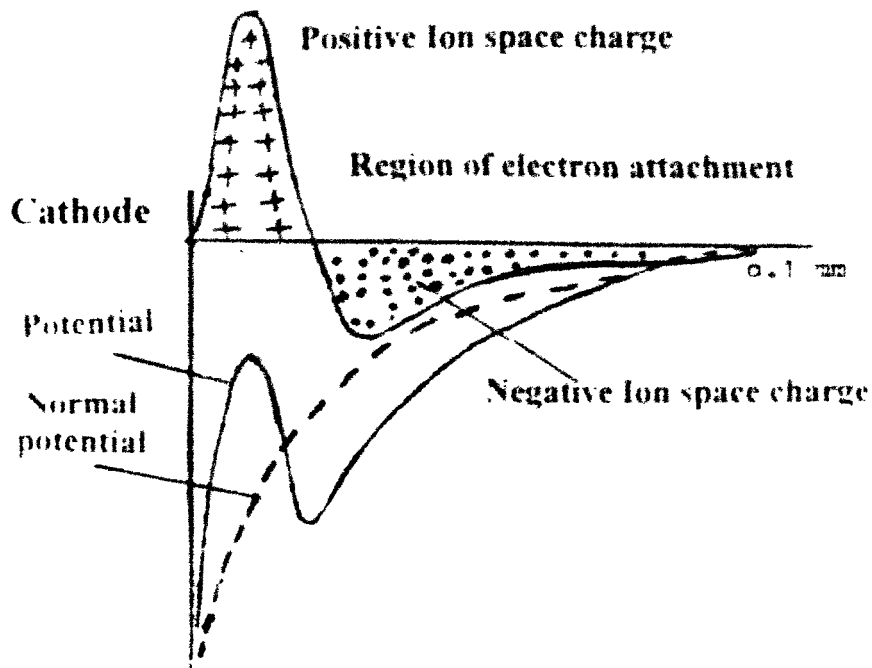
Fig. (9.7) shows the measured corona pulse repetition rates and pulse-height distributions at the indicated voltages for electrodes conditioned by prior discharges. The pulses appear intermittently with a low frequency of 100 Hz carrying a charge < 10 pC. Increasing the voltage increases the frequency to above 100 kHz as shown at 15.15 kV. The three distinct peaks evident at lower voltages (9.7 and 10.5 kV) probably correspond to discharges from the different spots or regions of the electrode. In general the negative corona was observed to be less reproducible than the positive corona.

The condition to be satisfied for corona inception is given by

$$\int_0^{d_0} (\alpha - \eta) dx = k$$

where k is a constant (~ 10) and d_0 is the distance at which the ionization coefficient equals the attachment coefficient, $\alpha = \eta$. Once corona is initiated it could be further enhanced by secondary electron emission from the cathode or photon emission in the gas. Thus, even at voltages much higher than that required to satisfy equation (9.15) the corona consists of predominantly small pulses of magnitude ~ 1 pC.

(a) Ionization occurs near the cathode



(b) Clearing of space charge

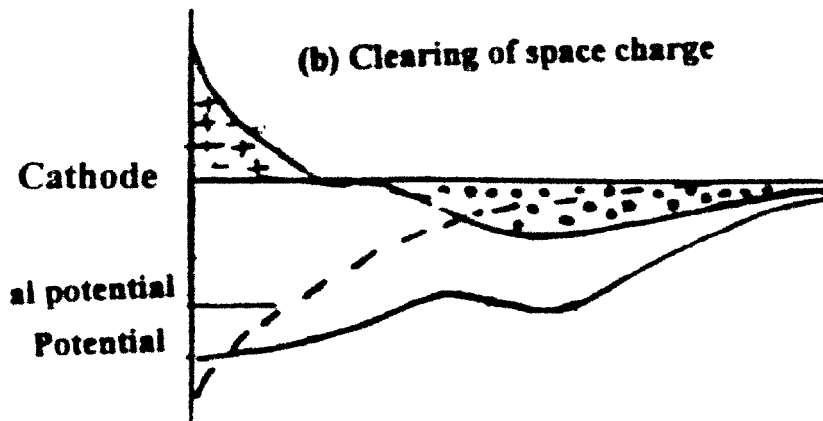


Fig. 9.5 Mechanism for the formation of the Trichel pulses from a negative point. (a) The top Figure shows the presence of positive ions closer to the electrode and the negative ions farther away. (b) Just before clearing of the space charge and restoration of the Laplacian field.

As in other gases, electron-attaching or not, the negative corona inception voltage is smaller than the inception voltage for positive corona. The reason for this phenomenon is partially due to the fact that the initiatory electrons for negative corona are found in a well defined high field region on the surface of the electrode. In contrast the initiatory electrons for positive corona originate in the volume, this volume being very small at the onset voltage. As the voltage is increased the volume increases with an increase in the detachment coefficient contributing to greater number of initiatory electrons.

9.5 BASIC MECHANISMS : POSITIVE CORONA

The corona characteristics are extremely polarity dependent and we have already explained that the positive corona inception voltage is higher than the negative inception voltage. The difference between the inception voltages increases with increasing divergence of the electric field. The corona from a positive point is predominantly in the form of pulses or pulse bursts corresponding to electron avalanches or streamers. This appears to be true in SF₆ with gas pressures above 20 kPa and from onset to breakdown voltages [van Brunt, 1981].

At low pressures < 50 kPa the intermittent nature of corona does not permit a definite frequency to be assigned and only an average corona current can be measured in the range of 0.1 nA-1 μ A. As the pressure is increased predominantly burst pulses are observed with a repetition rate of 0.1-10 kHz. The charge in an individual pulse is higher than that in a negative corona pulse. At higher pressures the time interval between pulse bursts becomes less than 2 μ s.

Near inception positive corona appears in the form of infrequent electron avalanches of low charge, ($q < 1$ pC). The initiatory electrons are probably due to collisional detachment of negative ions, though field detachment has also been proposed. At higher voltages and lower gas pressures the bursts occur rapidly forming a train of corona pulses. Fig. 9.7 compares the influence of polarity and ultraviolet radiation on the pulse discharge repetition rate for both polarities at 400 kPa.

Van Brunt and Leep (1981) draw the following conclusions for positive corona in SF₆.

- (1) As voltage is increased, positive corona appears as low-level electron avalanches of low repetition rate ($f < 1$ Hz) and then develops into avalanches or relatively large (10-100pC) streamer pulses that act as precursors to burst pulses.

- (2) At corona currents above about 0.1 nA corona pulses and/or pulse bursts have a repetition rate and mean amplitude that increases with increasing voltage (Fig. 8.20).
- (3) The average duration of positive corona pulses tends to increase with decreasing gas pressure and increasing applied voltage.

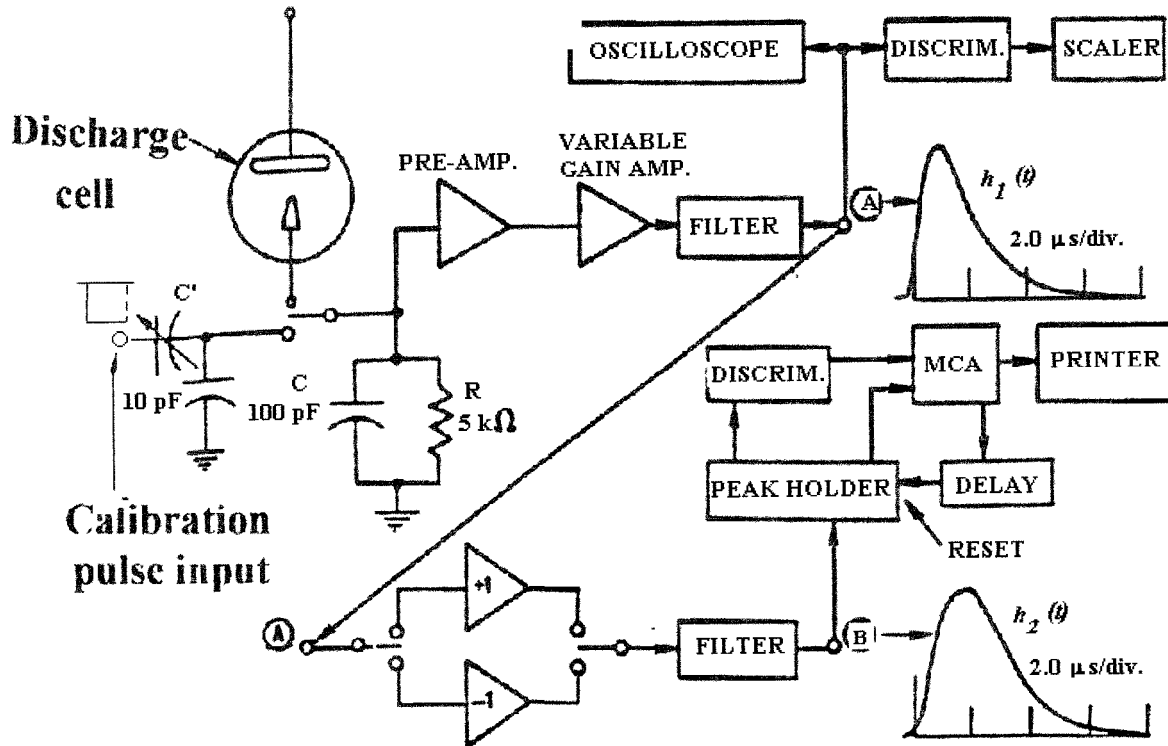


Fig. 9-6. System for measuring electrical characteristics of corona pulses. Shown also are the measured impulse responses $h_1(t)$ and $h_2(t)$ at points A and B where the pulse repetition rates and pulse height distributions are measured (Van Brunt and Leap, 1981; with permission of the American Physical Society.)

Under appropriate conditions of parameters like gas pressure, gap length, electrode dimensions etc. the burst pulses form into a glow region usually called Hermstein glow (Loeb, 1965). Though Hermstein thought that the positive glow occurs only in electron attaching gases, recent investigations have disclosed that non-attaching gases such as Ar, He and N₂ also exhibit the same phenomenon³¹.

The current due to the positive glow increases with the applied voltage (Fig. 9.8) and consists of nonlinear oscillations of high frequency ($10^5 - 10^6$ Hz). The positive glow can be sustained only in the presence of a fast replacement of electrons leaving the ionization region, and the mechanism of this fast regeneration is photoelectric action at the cathode and photo-ionization. Photoelectric action is the preferred mechanism in non-attaching

gases, whereas photo-ionization in the gaseous medium plays a dominant role in electronegative gases such as air. Soft x-rays have also been detected in N_2 (Yu et. al., 1999) contributing to the ionization of the gas.

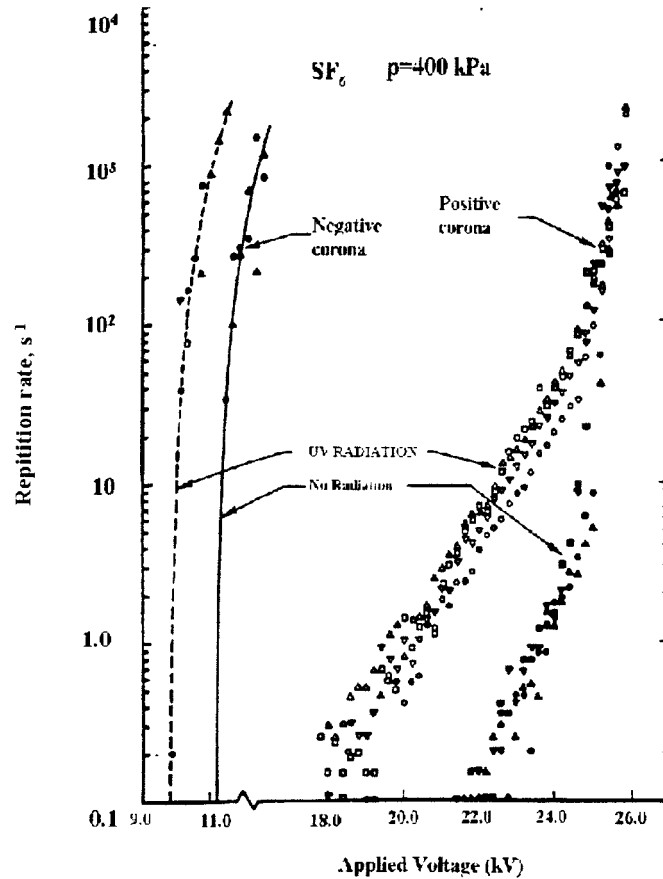


Fig. 9.7 Partial discharge repetition rate vs applied voltage for positive and negative point-plane dc corona in SF_6 at an absolute pressure of 400 kPa. Open symbols correspond to data obtained for a gap irradiated with UV radiation. Included are all pulses with a charge in excess of 0.05 pC (Van Brunt and Leep, 1981; with permission of American Institute of Physics).

9.6 MODELING OF CORONA DISCHARGE: CONTINUITY EQUATIONS

General comments on the methods available for modeling a discharge will be considered in section 9.7. Focusing our attention to the literature published since about 1980, the contributions of Morrow and colleagues³² and Govinda Raju and colleagues will be considered, because of the different approaches adopted for the theoretical study. The use of continuity equations provides the starting point for the method of Morrow; the temporal and spatial growth of charge carriers, namely electrons, positive ions, negative ions and excited species of metastables coupled with Poisson's equation are solved. Ionization, attachment, recombination, and electron diffusion are included for the growth

size, either one-dimensional form or radial coordinates, both for spherical and cylindrical coordinates are solved. It is assumed that there is no variation in the other coordinate directions.

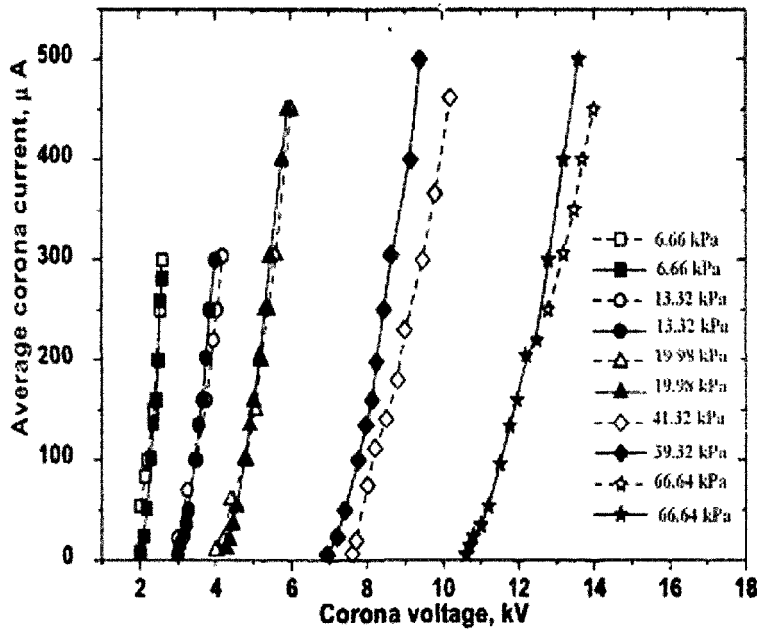


Fig. 9.8 Measured corona-voltage characteristics for positive corona in nitrogen at various gas pressures. Open and full symbols correspond to meshy and solid cathodes. Lines are guide to the eye. (Akishev et. al., 1999; with permission of Institute of Physics.)

The one-dimensional continuity equations for corona in oxygen are Kunhardt and Leussen, 1981):

$$\left. \begin{aligned} \frac{\partial N_e}{\partial t} &= N_e \alpha W_e - N_e \eta W_e - N_e N_p \beta - \frac{\partial(N_e W_e)}{\partial x} + \frac{\partial^2(DN_e)}{dx^2} \\ \frac{\partial N_p}{\partial t} &= N_e \alpha W_e - N_e N_p \beta - N_n N_p \beta - \frac{\partial(N_p W_p)}{\partial x} \\ \frac{\partial N_n}{\partial t} &= N_e \eta W_e - N_n N_p \beta - \frac{\partial(N_n W_n)}{\partial x} \end{aligned} \right\}$$

Here t is time, x the distance from the cathode, N_e , N_p , and N_n are the electron, positive ion and negative ion densities, respectively, and W_e , W_p , and W_n are the drift velocities of these particles, respectively. The swarm parameters of the gas are, ionization (α), attachment (η), recombination (β), and diffusion (D) coefficients. The mobilities are considered to be positive in sign for all particles. The continuity equations are coupled to

the Poisson's equation via the charge density. It is important to solve the Poisson's equations in three dimensions to allow for the radial extent of the charge distribution.

The last two equations of the set (9.16) are both first order and require only one boundary condition each. These are: (i) $N_p = 0$ at $x = d$, (ii) $N_n = 0$ at $x = 0$. The first equation of the set (9.16) is for electrons and it is of the second order requiring two boundary conditions. These are: (i) At the anode, i.e. at $x = d$, $N_e = 0$ and (ii) at the cathode, i.e. at $x = 0$, $N_e = N_e^p + N_e^i$ where N_e^p is the number of secondary electrons released due to the photoelectric action at the cathode and N_e^i is the number of secondary electrons released due to positive ion bombardment.

The current I in the external circuit due to the motion of electrons and ions between the electrodes is calculated according to

$$I = \frac{\pi r^2 e}{V_A} \int_0^d \left(N_p W_p - N_n W_n - N_e W_e + \frac{\partial(DN_e)}{\partial x} \right) E_L dx \quad (9.17)$$

The results of computations are discussed below.

The negative corona current at inception occurs in the form of a pulse having a rise time of about 10 ns (Fig. 9.9 a). The current in the pulse then decreases over a much longer period of about 1300 ns. Initially the electron multiplication in the Laplacian field is the dominant process and the influence of space-charge or the negative ions is negligible. At the end of this period the influence of space charge in distorting the electric field begins to be felt. Near the cathode the field is slightly enhanced due to the presence of positive ions, and further out it is somewhat depressed due to the accumulation of negative ion space charge. The electrons leaving the ionization zone are fast replenished ensuring the growth of the discharge. The light output increases with a weak diffuse form.

A prominent cathode fall region is formed immediately adjacent to the cathode, and almost zero field is formed within the plasma. The decrease of the field nearer the anode is attributed to space charge, which intensifies as the current in the pulse reaches a maximum. The current does not rise indefinitely because the feed back mechanism of the secondary electrons due to photoelectrons declines after reaching a maximum. The trailing edge of the corona pulse is due to the progressive decay of the discharge which allows the build up of the electric field in the low field region (Fig. 9.9 b). The current pulse is quenched because the low electric field in the plasma reduces the energy of the electrons to such an extent that three body attachment becomes dominant. Furthermore, the cathode fall region becomes reduced to such a short distance that insignificant current

the cathode fall region becomes reduced to such a short distance that insignificant current is generated from this region. Because of the low mobility of the negative ions, the current remains low and the structure of the space-charge fields changes only slowly with time between pulses.

The development and decay of a discharge may be summed up in the following steps:

1. $t \leq 26$ ns: Current multiplication in the Laplacian field initiates the negative corona pulse (A to B in Fig. 9.9).
2. $26 \leq t \leq 39$ ns: The feed back of secondary electrons, predominantly due to photoelectric action reaches a maximum and then decreases. The current pulse has a shape that is related to this mechanism (B to C). Photons and positive ions are generated in the same ionization region but the ions arrive at the cathode at a much later time. The secondary emission mechanism due to ions comes into play only during the decay phase of the pulse, at times of the order of ~ 100 ns.

The initial rise of the corona pulse has been experimentally observed to have a step³³ and the step is attributed to the longer time required for ions to drift to the cathode. In a recent theoretical investigation, however, Gupta, et al³⁴ have proposed that two mechanisms, namely photoelectric action and ion bombardment are not required to explain the observed step. A negative corona current pulse with the step on the leading edge is observed in the presence of ion-impact electron emission feed back source only. The step is explained in terms of the plasma formation process and enhancement of the feed back source. Ionization wave-like movement is observed after the step.

3. $39 \leq t \leq 70$ ns: The cathode sheath forms during the decay period of the current pulse (C to D). Due to a decrease in the replenishment of electrons falling below the critical value the discharge progressively decays. In addition to the decrease of replenishment of electrons, a number of other mechanisms are possible for the decay of current. The primary electrons move away from the negative point to the low field region where they form negative ions, thus reducing the current. Positive ions are absorbed by the cathode and reduce the space charge near the cathode and the current.
4. $70 \leq t \leq 131$ ns: The electron removal phase due to the formation of negative ions (D to E). At the end of this period the densities of electrons and negative ions are comparable.
5. $t > 131$ ns: Electrons are lost due to three body attachment, and the discharge current continues to decay for longer periods.

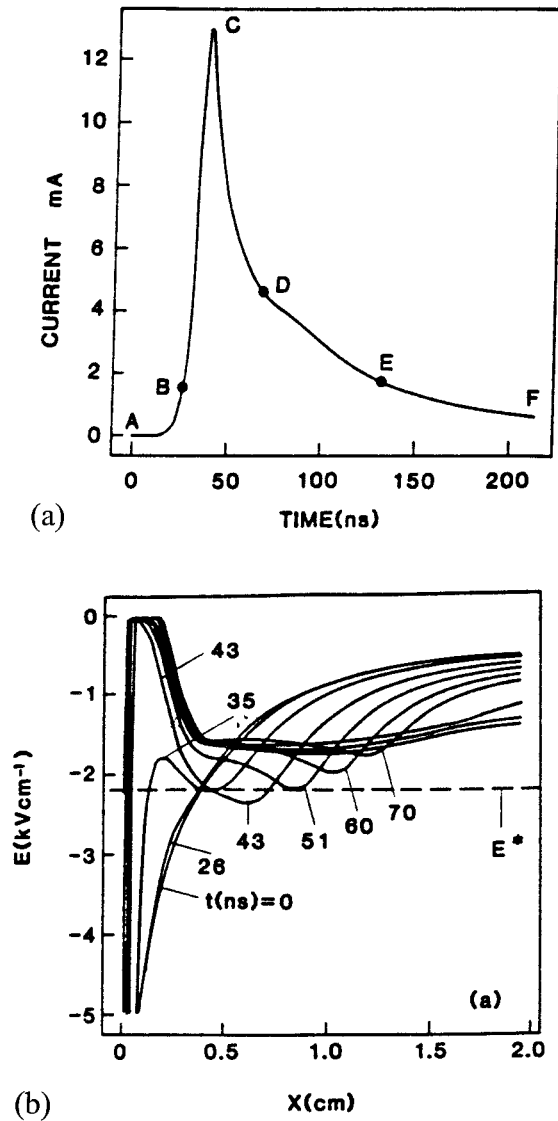


Fig. 9.9 (a) Computed current in the external circuit vs time in a negative point-plane gap in oxygen. (b) Electric field vs. position at the times shown (ns) after the release of primary electrons. $x = 0$ is the cathode. E^* is the field at which the ionization coefficient is equal to the attachment coefficient (Morrow, 1985; with permission of American Physical Society.)

Morrow has added significantly for our present knowledge of corona phenomena. Use of continuity equations has an implied equilibrium assumption, i.e., the electron, ion transport coefficients and rate coefficients are only a function of the local reduced electric field E/N . Sigmond and Goldman (1978) have pointed out that this assumption becomes questionable in very high or very inhomogeneous fields. To investigate these effects we have to adopt a different simulation technique, which is possible by the use of the Monte Carlo method.

9.7 NON-EQUILIBRIUM CONSIDERATIONS

Generally, in a uniform electric field remote from boundaries, the macroscopic parameters, such as the drift velocities and ionization and attachment coefficients, are dependent on the ratio E/N because the energy gain from the field is balanced by the energy lost in collisions. However when the field changes rapidly with position or time, this energy balance is disturbed and the transport parameters and coefficients may differ from the predictions made on the basis of the local field. Because of the complexity of the non-equilibrium behaviour the swarm parameters have been analyzed in non-uniform fields in several gases³⁵ both by the Monte Carlo method and the diffusion flux equations. Table 9.1 summarizes some recent investigations.

Table 9.3
Monte Carlo studies in non-uniform fields [35]

Author	Gas	Field Configuration	Field Slope
Boeuf & Marode	He	Decreasing	Two
Sato & Tagashira	N ₂	Decreasing	one
Moratz et. al.	N ₂	Decreasing & increasing	Four
Liu & Govinda Raju	SF ₆	Decreasing & increasing	one

(Liu and Raju, 1992; with permission of IEEE ©.)

In considering the effects of non-uniformity on the swarm parameters, a distinction has to be made on decreasing electric field or increasing electric field along the direction of electron drift. Liu and Govinda Raju [1992] have found that α/N is lower than the equilibrium value for increasing fields and is higher in decreasing fields (Fig. 9.7), with the relaxation rate depending upon the field slope, β . The relaxation rate has been found to depend upon not only the field slope but also on the number gas density. The effects of changes in field slope and pressure, acting alone or together are discussed below.

1) *Effect of Field slope (β^2)* : To ensure that the electrons are in equilibrium before entering the non-uniform region, the simulation includes a region of uniform electric field at both the cathode and the anode. The initial electrons released from the cathode are required to travel a minimum distance before attaining equilibrium as they enter the non-uniform region. The ionization coefficients are higher than the uniform field values for decreasing field slope and vice versa for increasing fields. The deviations from the equilibrium values are also higher, particularly in the mid gap region for higher values of

β^2 . Both increasing fields and decreasing fields influence the swarm parameters in a consistent way, though they are different from the uniform field values.

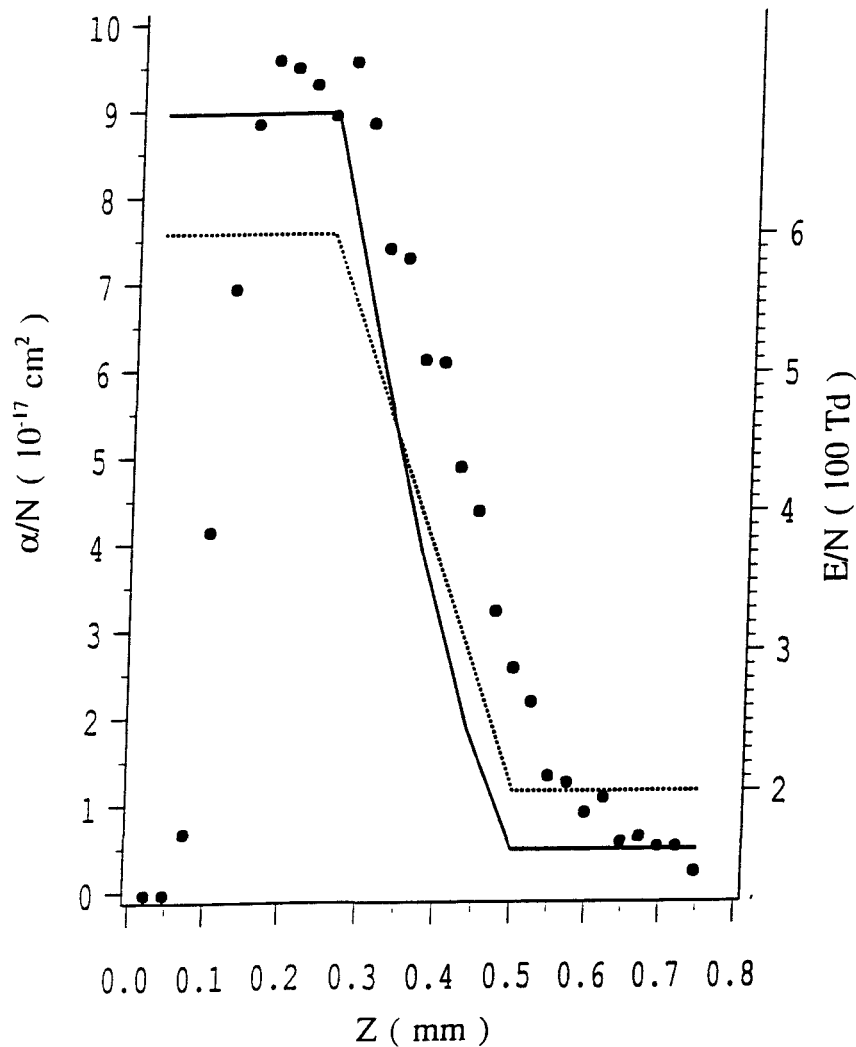


Fig. 9.10 Ionization coefficients in SF_6 in non-uniform field gap in a decreasing field slope of $\beta^2=16$ kTd/cm at $N= 2.83 \times 10^{23} \text{ m}^{-3}$. Symbols are computed values. Closed line for equilibrium conditions. The reduced electric field is shown by broken lines (Liu and Raju, 1997; IEEE ©.)

In non-uniform fields, although the energy gain from the field changes instantly with the changing field, the energy loss governed by collisions is a slower, non local process. Also the collisional energy loss is dependent on the electron energy and different parts of the electron energy distribution will readjust to changing field with different rates. Fig. (9.11 a) shows the energy distribution function, $f(\epsilon)$, at 400 Td in uniform, decreasing and increasing fields at the midpoint of the gap [(Liu and Raju, 1997)]. It is clear that relatively more electrons are distributed in the high energy range for the decreasing field,

and fewer electrons for the increasing field, compared with the uniform situation. The lower portion of Fig. (9.11) shows the energy distribution function along the non-uniform gap for a decreasing field at $N = 2.83 \times 10^{23} \text{ m}^{-3}$, $\beta^2 = 8 \text{ kTd/cm}$.

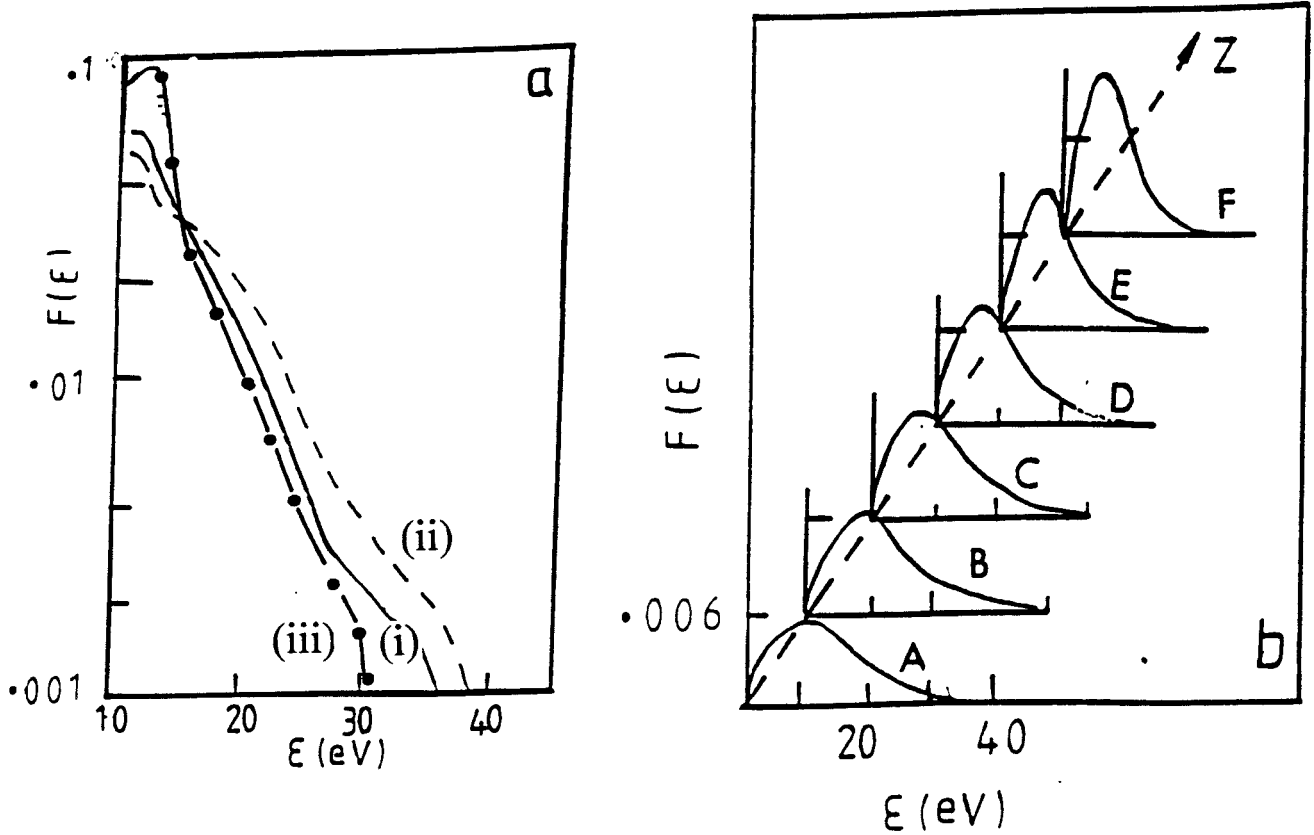


Fig. 9.11. (a) Energy distribution function in uniform and non-uniform fields at $E/N = 400 \text{ Td}$ corresponding to the mid point of the gap, $N = 2.83 \times 10^{23} \text{ m}^{-3}$, (i) uniform field (ii) decreasing field (iii) increasing field. (b) Energy distribution function along the non-uniform gap in a decreasing field. A: $z = 0.5 \text{ mm}$, 600 Td; B: $z = 0.6 \text{ mm}$, 520 Td; C: $z = 0.7 \text{ mm}$, 440 Td; D: $z = 0.8 \text{ mm}$, 360 Td; E: $z = 0.9 \text{ mm}$, 280 Td; F: $z = 1 \text{ mm}$, 200 Td [Liu and Raju, 1992]. (With permission of IEEE).

As z increases from 0.5 mm to 1 mm, E/N decreases from 600 Td to 200 Td, and the peak of $f(\epsilon)$ moves toward low energy range. From such analyses of the distribution function at various reduced electric fields, E/N , we can explain the fact reduced ionization coefficients, α_d/N , in decreasing fields are higher than the equilibrium values, i. e., $\alpha_d/N > \alpha/N > \alpha_i/N$, where α_i is the ionization coefficient in increasing fields.

We have already referred to the polarity dependence of the corona inception voltage, V_c , (Fig. 8.15) in non-uniform fields. The corona inception voltage for negative polarity is lower than that for positive polarity and the results previously discussed support the following mechanism for corona. With negative polarity, the electrons experience decreasing fields as they move toward the anode and the actual ionization coefficients, α_d , are higher than the equilibrium values. Furthermore, the magnitude of the difference between the actual and equilibrium values, $(\alpha_d - \alpha)$, is higher for the negative polarity. The corona inception voltage which is dependent on the exponential of α_d is therefore higher for the positive polarity voltage than that for the negative polarity.

The attachment coefficients are also affected by the changing field when compared with equilibrium values. With changing field, the electrons cannot catch up with the faster decreasing field and have energies greater than those dictated by the local field. This means that relatively more electrons are distributed in the high energy tail, causing more ionizing collisions (Fig. 9.11). These ionization collisions generate new electrons with low energy and these electrons attach to SF_6 molecules and increase the attachment coefficient. The observed sharp decrease of the attachment coefficients near the anode is probably caused by the gradual disappearance of the backward directed electrons arising from electron absorption by the anode. With regard to the other swarm parameters the mean energy and drift velocity rise near the anode and the attachment coefficients fluctuate, particularly with higher β^2 , possibly due to the small number of attachment coefficients.

2) *The effect of gas number density (N):* The gas number density is expected to have an effect on the non-equilibrium behavior due to the fact that the relaxation rate is dependent on the collision rate. At higher gas densities more collisions occur within the sampling distance and the electron swarm will readjust itself faster as appropriate to the applied field. This results in a coefficient that deviates from the equilibrium value by a smaller amount. The mean energy at the first part of the non-uniform gap is lower than the equilibrium value because the larger number of ionization collisions results in loss of more energy. The anode effect is observed by a sharp decrease of η/N and a sharp rise in the mean energy.

3) *The effect of simultaneous change in β^2 and N:* Low N and high field slopes enhance the non-equilibrium behaviour of the electron swarm. An important consideration is whether the rate of change of the coefficients remains the same if β^2/N remains the same. By considering the three sets of individual values of β^2 and N such that their ratio remains the same, it has been found that individual changes in each parameter do not affect α/N and η/N as long as the ratio is not affected. The same observations are also

qualitatively true for the mean energy and drift velocity though the change in them is not as significant as the change in α/N and η/N . This is reasonable because the change in the energy distribution affects the latter two parameters more than the former.

4) *Electron and ion distribution*: Space charge plays an important role in determining the electric field in the gap. as the previous discussions have clearly demonstrated. Fig. 9.9 shows the distribution of electrons and ions in the gap, both in a uniform field and a non-uniform field. The essential features of the differences in the distribution of charges may be summarized as follows:

- a. In a uniform field gap (Fig. 9.12a) the electron density increases exponentially uneventfully. However in decreasing fields (Fig. 9.9b) the electron density reaches a peak at approximately the mid gap region. This is due to the combination of two opposing factors: (1) The electric field, and therefore the ionization coefficient, decreases. (2) The number of electrons increases exponentially. In increasing field, both these factors act cumulatively and N_e increases initially slowly but very rapidly as the electrons approach the anode. It is easy to recognize that the two situations of non-uniform field correspond to negative and positive coronas.
- b. The total number of negative ions is denoted by N^- and the individual contribution of each species are identified in Fig. (9.12a). In both uniform and non-uniform electric fields the ion density oscillates and is possibly due to relaxation process of the electron energy distribution as suggested by Itoh, et. al.³⁶.
- c. The negative ion density in the non-uniform field shows a peak, first increasing till the end of the non-uniform region, then decreasing in the low field region because of the decrease in the total number of electrons in the low field region. There is a shift between the peak of the electron density and the negative ion density. Though the field has attained the critical value corresponding to $\alpha=\eta$ multiplication continues to occur because of the non-uniform equilibrium effects, thereby increasing N^- . Beyond the peak the reduced number of electrons yield reduced negative ions.

9.8 MONTE CARLO SIMULATION: NEGATIVE CORONA IN SF₆

The Monte Carlo technique has been extended to the study of negative corona and development of streamers³⁷. A flow diagram used for the purpose is shown in Fig. 9.13. The initial electrons are emitted from the cathode according to a cosine distribution because the emission occurs on only one side of the electrode. The Laplacian field in the gap is

$$E_L(z) = \frac{2Vd}{\ln\left[\frac{4d}{r_c}\right]\left[d(2z + r_c) - z^2\right]} \quad (9.18)$$

where z is the space coordinate, V the applied voltage and r_c the radius of the cathode tip. The energy gain of the electrons in a small time interval Δt is governed by the equations of motion.

Whether a collision between an electron and a gas molecule occurs or not is decided by generating a random number R uniformly distributed between 0 and 1. A collision is deemed to occur at the end of a time step if $P > R$ where P is the probability of collision. In the event of an elastic collision the fractional loss of energy is $2m/M'$ where m and M' are masses of electron and SF_6 molecule. The direction of electron motion after a collision is determined according to equations of motion. To reduce the CPU time of the simulation of the motion of a large group of electrons during $\sim 50\text{ns}$, Liu and Govinda Raju (1994) assume that the electrons move in one dimension in space with a velocity which has three components (V_x, V_y, V_z). In the simulation of a corona discharge time step and the cell size should be paid great attention since the electric field is steep close to the smaller electrode. Also the accumulation of the space charge causes the field near the cathode to change abruptly; therefore smaller cell size and time steps are required.

The length of field intensive region varies with various voltages and gap separations and it is varied for each situation.

$$T_m = \frac{1}{NQ_T W_e} \quad (9.19)$$

where Q_T is the total collision cross section and W_e is the electron drift velocity. The time step Δt used to calculate the motion of electrons and space charge field is chosen to be very small ($\Delta t \ll T_m$) and Δt may be different for different applied voltages. In negative coronas Δt is in the range of 0.5 to 1 ps.

At each time step, the new position and energy is calculated according to the equation of motion. New electrons, positive and negative ions may be produced by ionization, photo-ionization and attachment collisions. At the end of each time step, the space charge field is calculated from the Poisson's equation as a function of charge distribution and is stored for use in the next time step.

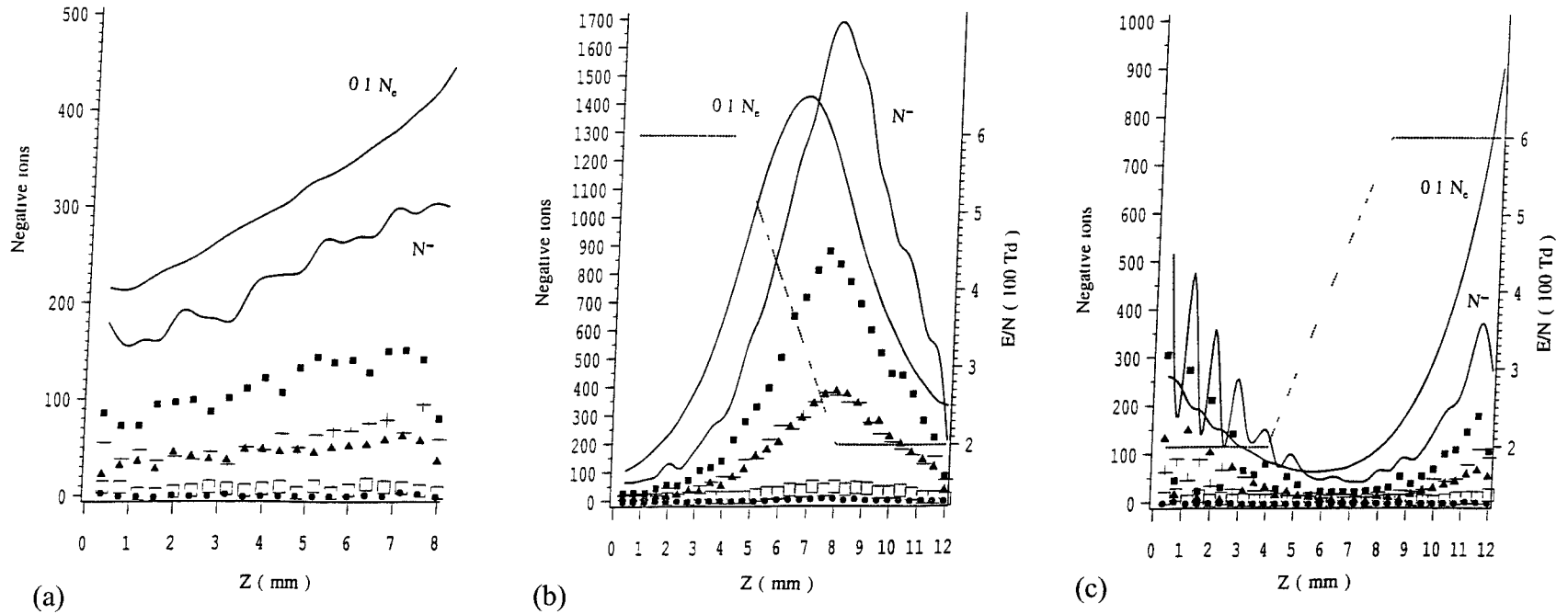


Fig. 9.12 Electron and ion distribution in the gap in SF_6 . (a) Uniform electric field (400Td). Ion species are: closed square- SF_6^- , closed triangle- SF_5^- , Plus- SF_4^- , closed circle- F_2^- ; Arbitrary units. The electron density is multiplied by 0.1. (b) decreasing electric field, symbols same as (a). (c) increasing electric field, symbols same as (a). (Liu and Raju, 1994; IEEE ©.)

The space charge field in k^{th} cell is given by

$$E_k = E_{(k-1)} + \frac{1}{2}[\Delta E_{(k-1)} + \Delta E_k]; \quad 1 \leq k \leq M \quad (9.20)$$

where M is the total number of cells in the low field region. The integration of the space charge field over all cells should be zero (space charge produces no external voltage on the gap). The final field is the sum of the applied Laplacian field and the space charge field.

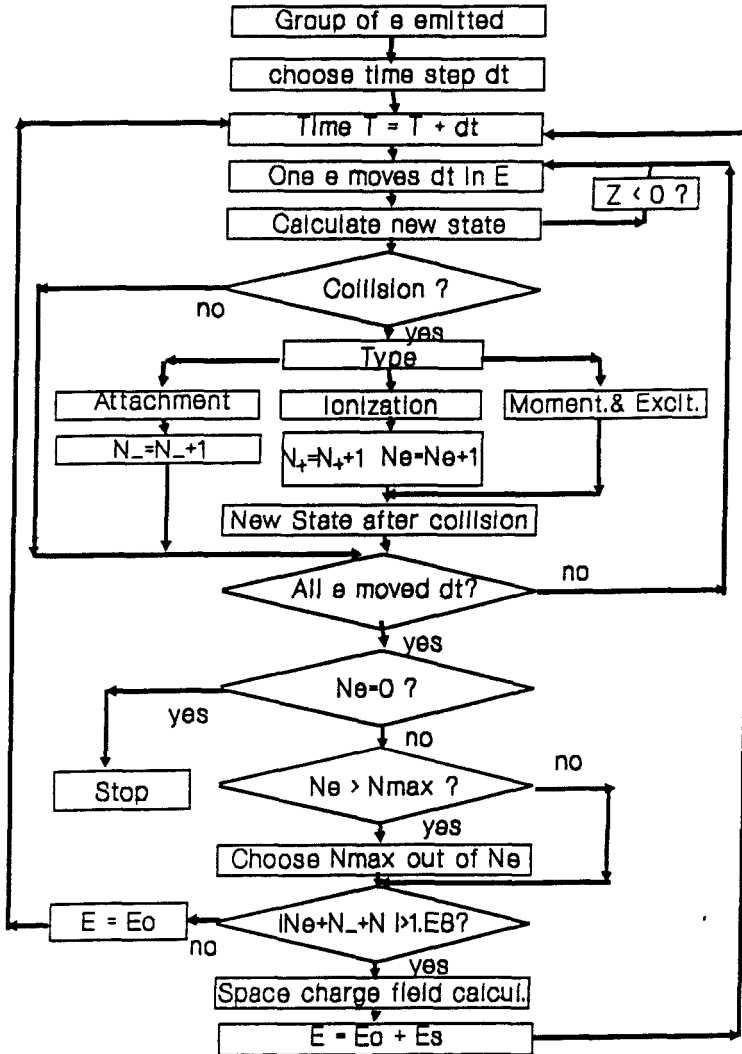


Fig. 9.13 Flow diagram of Monte Carlo simulation of corona discharge . e =electron, N_e = number of electrons, N_+ = number of positive ions, N_- = number of negative ions (Liu and Raju, 1994, IEEE ©.)

The current density J in the external circuit due to the motion of electrons, and ions between the electrodes is calculated using Sato's equation

$$J = \frac{e}{V} \int [N_p W_p - N_n W_n - N_e W_e] E_L dz \quad (9.21)$$

where the subscripts e, n and p stand for electron, negative ion and positive ion, respectively. Fig. (9.14a) shows a single current pulse at the onset of corona and the current is of avalanche type with a single pulse.

With increasing voltage the current density increases and the current now becomes a streamer type with more than one pulse contributing to the current. The time at which the peak occurs becomes shorter due to the faster development of the electron avalanche in a higher field. The pulse shape obtained (Fig. 9.14a) is similar to those observed by Van Brunt and Leap (1981) and Morrow³⁸. The larger pulses are usually followed by a long tail, or a burst of lower level pulses which is characteristic of positive corona.

The total field distribution in the gap is shown in Fig. (9.14b). The space charge distortion begins at 2.8 ns and increases up to 5.95 ns. It then remains unchanged for ~5 ns (not shown) because no more ions are produced after this time. The smallest electric field is only 0.4 V/cm. A comparison with Fig. (9.14b) shows that the space charge distortion occurs in SF₆ much earlier than in oxygen because the attachment in the former gas is much more intensive.

Fig. (9.14c) shows the development of subsequent avalanches. The second avalanche gives rise to the third avalanche due to photo-ionization at 1.6 ns and in the time interval 1.6-2.3 ns the third avalanche grows much faster because of intense field near the cathode. After about 4.5 ns all the electrons are in the low field region and the avalanches die out soon thereafter.

9.9 MONTE CARLO SIMULATION: POSITIVE CORONA IN SF₆

As a preliminary to the discussion we again refer to the experimental measurements of Van Brunt and Leap (1981) who have contributed significantly to the advancement of understanding positive corona. The studies were carried out at relatively high pressure of 50 ~ 500 kPa in SF₆. Positive corona pulses appear at onset as low-level electron avalanches that, contain relatively low charge ($q < 1$ pC). The corona inception current is less than 0.1 nA. The frequency of the pulses vary from about 0.3-5 kHz depending upon the voltage and corona current. At higher voltages, the pulses develop into large

streamers usually followed by a burst of many small pulses. The burst characteristics of positive corona show a definite dependence on pressure and voltage which is evident in the pulse height distribution data. Comparing with negative corona studies, positive corona develops much more slowly and has a higher inception voltage as expected (Fig. 9.7).

The simulation technique shows that the initial current pulse is very fast with a half maximum amplitude of ~ 0.3 ns. The electrons are absorbed by the anode very fast; during collision photo-ionization occurs and the secondary electrons are produced leading to further avalanches. The positive ions are left behind leading to a fast build up of space charge³⁹. The space charge field depresses the applied field at the anode and a 'spike' is produced in the electric field as fast as ~ 0.5 ns. The spike is attributed to the high density of positive charges in the streamer head which propagates toward the cathode. The net positive charge behind the streamer front extends to the anode.

The streamer front moves very rapidly with a velocity of $\sim 8 \times 10^6$ m/s and as it progresses into the gap the electric field remains at the critical value, E^* . There is less voltage remaining at the streamer head and eventually there is insufficient voltage at the streamer tip to sustain its progress. The electron density is constant through the length of the streamer but farther away from the tip it declines rapidly. As the streamer progresses into the gap the region of constant electron density also extends into the gap. Outside this region, which is towards the cathode, ionization slows down and the recombination causes the positive ion, negative ion and electron densities to fall rapidly from their previously high values.

A further elucidation of the positive corona mechanism is obtained by the Monte-Carlo simulation⁴⁰. The corona inception occurs in the form of pulses. The shape of the current pulse obtained is similar to the experimental observations of Van Brunt and Leap (1981) with multiple peaks except that their duration of pulse is much longer: ~ 30 ns compared to the present duration of ~ 5 ns.

The development of the secondary avalanches is due to photo-ionization and occurs on the cathode side of the electron avalanche. Here the field is intensified whereas the field between the avalanche head and the point electrode is decreased. This is clearly shown in Fig. (9.14c) where avalanche #2, the parent avalanche, is smaller than the progeny avalanche, #3. The influence of the polarity in secondary avalanche development may be discerned from comparing with Fig. (9.15); the field intensification regions are different.

The differences between positive and negative coronas are shown in Table 9. 4.

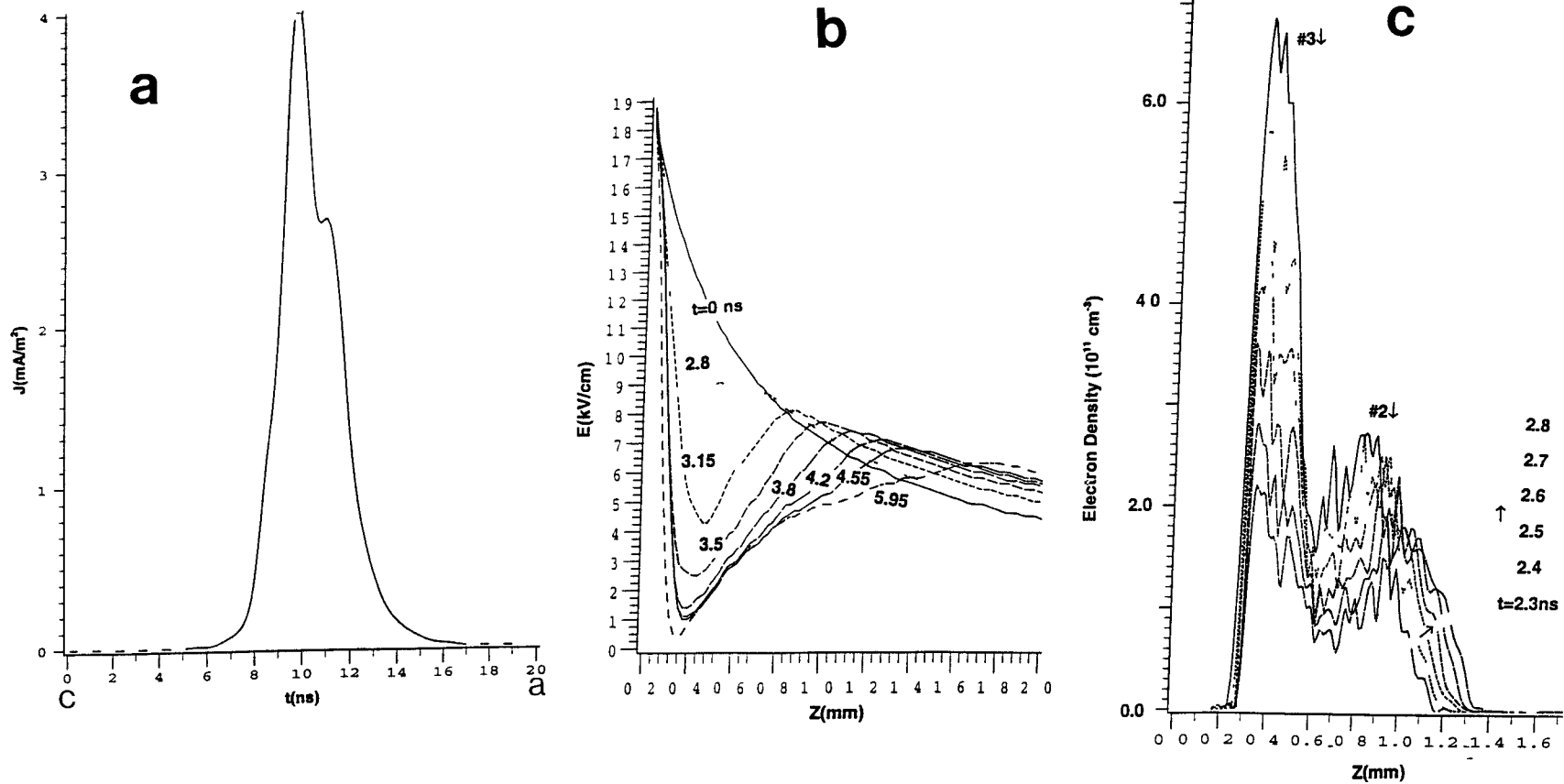


Fig. 9.14 Development of negative corona pulses in SF₆ at $N = 2.12 \times 10^{24} \text{ m}^{-3}$ (a) current due to a single pulse, $V=2.4 \text{ kV}$ (b) electric field in the gap at various times, $V=3.0 \text{ kV}$ (c) electron density distribution at $2.3 \leq t \leq 2.8 \text{ ns}$, $V=3.5 \text{ kV}$. Liu and Raju, 1994; with permission of IEEE ©.)

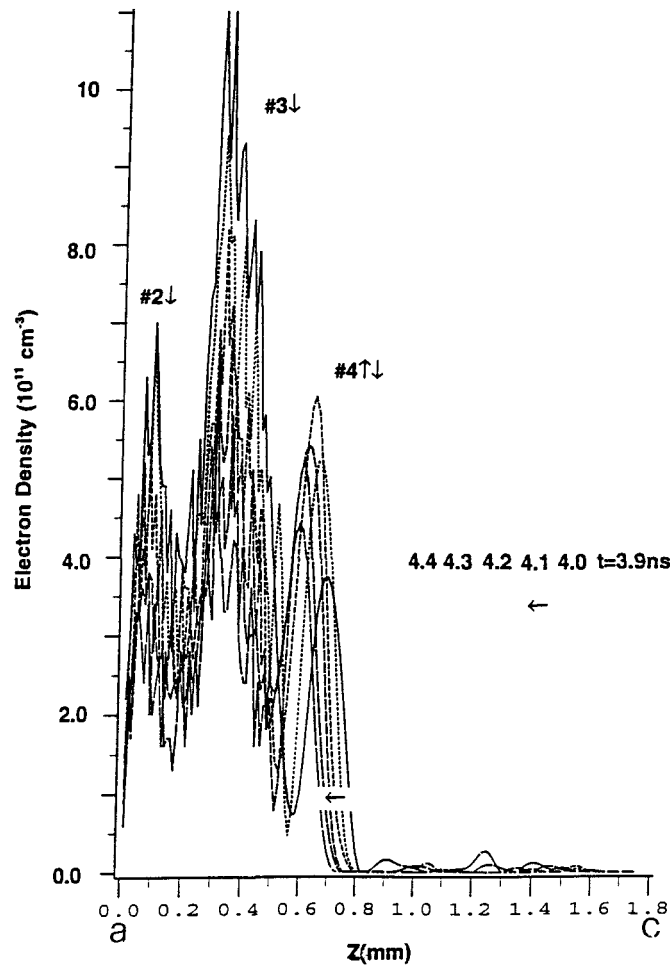


Fig. 9.15 Electron density distribution in positive corona pulses. The sequence of development of secondary pulses development should be compared with figure 14(c) for negative polarity. Applied voltage is 4.0 kV and $3.9 \leq t \leq 4.4$ ns. (Liu and Raju, 1994; with permission of IEEE.)

Table 9.4
A Comparison of Positive and Negative Coronas in SF₆

	POSITIVE CORONA	NEGATIVE CORONA
Effect of space charge on total field	(a) Depressed near anode (b) Enhanced in the rest of region	(a) Enhanced near the cathode (b) Enhanced near the anode (c) Depressed in the midgap region
Second avalanche	(a) Anode side of the primary avalanche	(a) Cathode side of the primary avalanche
Subsequent avalanches	Cathode side of the previous avalanche	Cathode side of the previous avalanche
Concentration of negative ions in the gap	Negligible	Appreciable
Concentration of positive ions in the gap	Appreciable	Appreciable

9.10 CONCLUDING REMARKS

Comparing the continuity equations method with the Monte Carlo method, the former is concise and consumes less CPU time. However more assumptions are implicit and it is not as straight forward as the Monte Carlo method. Further, the continuity equation method has the disadvantage that all the swarm parameters should be known prior to the analysis. Usually these parameters are assumed to be in equilibrium with the field. Since the streamer mechanism is the result of space charge distortion with the total electric field may be as large as 5 times the average field. The field slope, which has been shown to be significant, may be quite large. These aspects need to be viewed against the longer CPU time required by the Monte Carlo method.

The range of experimental conditions and electrode geometries that are encountered in practice or under laboratory experimental conditions are so large that it is not possible to take into account all the parameters that determine the details of the discharge development. Further, the modelling process requires the initial and boundary conditions to be set up which may not be exact and require inordinate long computation time. However the advances in modern computing techniques and faster processing of various steps have led to success in simulating the discharge process, which go hand in hand with the experimental results.

9.11 REFERENCES

- ¹ R. S. Sigmond, "Corona Discharges", Chapter 4 in J. M. Meek and J. D. Craggs, "Electrical Breakdown of Gases", John Wiley & Sons, New York, 1978.
- ² L. B. Loeb, "Electrical coronas", University of California Press, 1965.
- ³ G. R. Govinda Raju and R. Hackam, J. Appl. Phys., **52** (1981) 3912.
- ⁴ J. Liu, Ph. D. Thesis, University of Windsor, 1993.
- ⁵ E. E. Kunhardt and L. H. Luessen, (Ed), article by L. C. Pitchford, "Electrical Breakdown and Discharges in Gases", Plenum Press, New York, 1981, pp. 313.
- ⁶ H. Tagashira, Y. Sakai and S. Sakamoto, J. Phys. D; Appl. Phys. **10** (1977) 1051.
- ⁷ J. Liu and G. R. Govinda Raju, Can. J. Phys., **70** (1993) 216.
- ⁸ J. Liu and G. R. Govinda Raju, IEEE Trans. on DIE & EI, **2** (1995) 1004.
- ⁹ R. D. Hake Jr., A. V. Phelps, Phys. Rev., **158** (1962) 70. Only valid for low E/N.
- ¹⁰ H. Myers, J. Phys.B., At. Mol. Phys., **2** (1969) 393-401. Attachment cross section is derived.
- ¹¹ H. K. Wagner, Z. Physik., **241** (1971) 258. Curve fitting to experimental data.
- ¹² J. Lucas, D. A. Price and J. Moruzzi, J. Phys. D.: Appl. Phys., **6** (1973) 1503. Valid for low E/N.
- ¹³ K. Masek, Czech. J. Phys., **25** (1975) 686. Valid for low E/N.
- ¹⁴ K. Masek, T. Ruzicka and L. Laska, Czech. J. Phys., B., **27** (1977) 888. Neglects attachment and dissociation.
- ¹⁵ K. Masek, L. Laska and T. Ruzicka, J. Phys. D.,: Appl. Phys., **10** (1977) L25.
- ¹⁶ T. Taniguchi, H. Tagashira and Y. Sakai, J. Phys. D.: Appl. Phys., **11** (1978) 1757. Only three body attachment calculated.
- ¹⁷ G. Gousset, C. M. Ferrir, M. Pinheiro, P. A. Sa, M. Tanzeau, M. Vialle and J. Loureiro, J. Phys. D.: Appl. Phys., **24** (1980) 290. No attachment co-efficient, emphasis on heavy particle.
- ¹⁸ T. Taniguchi, H. Tagashira, I. Okada and Y. Sakai, J. Phys.D.: **11** (1978) 2281.
- ¹⁹ G. Schaffer and P. Hui, J. Comp. Phys., **89** (1990) 1.
- ²⁰ J. Liu and G. R. Govinda Raju, IEEE Trans. on EI, **28** (1993) 261.
- ²¹ I. D. Chalmers, H. D. Duffy and D. J. Tedford, Proc. Roy. Soc., London, A, **329** (1972) 171.
- ²² A. J. Davies, Proc. IEE, Pt. A., **133** (1986) 217.
- ²³ J. P. Novak and R. Bartnikas, J. Appl. Phys., **62** (1987) 3605.
- ²⁴ J. P. Novak and R. Bartnikas, J. Phys. D.: Appl. Phys. **21** (1988) 896.
- ²⁵ J. P. Novak and R. Bartnikas, J. Appl. Phys., **64** (1988) 1767.
- ²⁶ J. P. Novak and R. Bartnikas, IEEE Trans. on Plasma Sci., **18** (1990) 775.
- ²⁷ S. K. Dhali and A. K. Pal, J. Appl. Phys., **63** (1988) 1355.
- ²⁸ S. K. Dhali and P. F. Williaams, J. Appl. Phys., **62** (1987) 4696.
- ²⁹ (a) J. E. Jones, J. Phys. D., Appl. Phys., **33** (2000) 389.

-
- (b) A. A. Al-Arainy, S. Jayaram, J. D. Cross, 12th International Conference on Conduction and Breakdown in Liquids, Italy, July 15-19, 1996.
- ³⁰ R. J. Van Brunt and D. Leap, J. Appl. Phys. **52** (1981) 6588.
- ³¹ Yu. S. Akishev, M. E. Grushin, A. A. Deryugin, A. P. Napartovich, M. V. Pan'kin and N. I. Trushkin, J. Phys. D., Appl. Phys., **32** (1999) 2399.
- ³² R. Morrow, J. Phys. D., Appl. Phys., **30** (1997), 3099.
- ³³ M. Cernak and T. Hosokawa, Japan. J. Appl. Phys., **27** (1988) 1005.
- ³⁴ D. K. Gupta, S. Mahajan and P. I. John, J. Phys. D: Applied Phys. **33** (2000) 681.
- ³⁵ For a list of references see J. Liu and G. R. Govinda Raju, IEEE Trans. on Plas. Sci., **20** (1992) 515.
- ³⁶ H. Itoh, M. Kawaguchi, K. Satoh, Y. Miura, Y. Nakao and H. Tagashira, J. Phys. D; Appl. Phys. **23** (1990) 299.
- ³⁷ J. Liu and G. R. Govinda Raju, IEEE Trans. on DIE & EI, **1** (1994) 520-529.
- ³⁸ R. Morrow, Phys. Rev., A, **32** (1985) 1799.
- ³⁹ R. Morrow, IEEE Trans. on DIE. & EI, **26** (1991) 398.
- ⁴⁰ J. Liu and G. R. Govinda Raju, IEEE Trans. on DIE & EI, **1** (1994) 530.